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**AUTOMATED FIBER PLACEMENT  
OF ADVANCED MATERIALS  
(PREPRINT)**

**Vernon M. Benson and Jonahira Arnold**



**APRIL 2006**

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//Signature//

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JONAHIRA ARNOLD, Program Manager  
Structural Materials Branch  
Nonmetallic Materials Division

//Signature//

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TIA BENSON TOLLE, Chief  
Structural Materials Branch  
Nonmetallic Materials Division

//Signature//

---

PERSIS A. ELWOOD, Deputy Chief  
Nonmetallic Materials Division  
Materials and Manufacturing Directorate

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# **AUTOMATED FIBER PLACEMENT OF ADVANCED MATERIALS**

Vernon M. Benson (ATK Space Systems, Clearfield, Utah 84016)  
Jonahira Arnold (AFRL/MLBCO, Dayton, OH 45433)

## **ABSTRACT**

As Composite Materials expand into higher temperature ranges they generally become increasingly more difficult to process with today's proven automated technologies. Automated Fiber Placement has become a standard process for fabricating large complex epoxy skins and shells. Fiber Placement with higher temperature materials, BMIs, and higher service temperature materials, has proven more difficult. Placement of BMIs on the Joint Strike Fighter (JSF) Program and other applications has presented some new challenges for the equipment and process. ATK has been working with the Air Force Research Laboratory to foster improvements in the BMI materials and in the fiber placement processing techniques to achieve rates comparable to Epoxy placement rates. This paper will concentrate on the recent advancements in BMI Materials for Fiber Placement and advancements in fiber placement processing techniques.

**KEY WORDS:** Fiber Placement/Automated Tow Placement (ATP), High Temperature Composite Materials/Structures, Resin/Materials – Bismaleimide (BMI)

## **1. INTRODUCTION**

Composite Materials offer great performance advantages to many products in our world today. One of the factors that keep composites from being more universally used is the overall cost of fabrication. The materials are generally higher in cost than most materials they compete with and fabrication labor can be much higher as well. This project is targeted at improving advanced composite materials such as Bismaleimides (BMIs) for automated processing, and improving the automated fiber placement process to better accept these higher temperature materials. The desired result of these material and process improvements being higher material deposition rates with automated fiber placement equipment.

Several companies, including ATK Space Systems (ATK), have been involved in developing lower cost manufacturing technologies for composites. One of these automation technologies (pioneered by ATK) that has been and continues to be very successful is Automated Fiber Placement (FP or AFP). Fiber placement of epoxy materials has become an accepted production process for many structures. More recently the use of higher temperature materials for structures, such as the use of BMI's on the F35 Joint Strike Fighter (JSF), have challenged the standard fiber placement process due to several material handling characteristics.

The quest for higher and higher temperature performing materials has taken the composite material suppliers into Cyanate Esters, BMIs, Polyimides, etc. As the temperature performance goes up, the processing characteristics of these materials have generally increased in difficulty,

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as compared to Epoxies. This has led to some disappointment with overall throughput of material in the AFP process on product such as the F35 Wing Skins using BMI prepreg material.

The work discussed in this paper will deal with recent improvements in BMI materials for automated fiber placement and improvements in the fiber placement process itself to better accommodate these higher temperature materials.

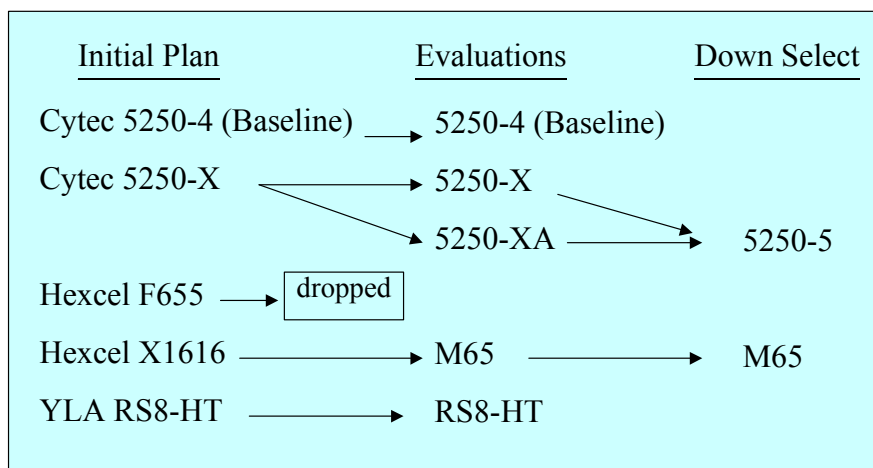
ATK received a contract from the Air Force Materials Research Lab in Dayton, Ohio to evaluate several high temperature composite materials for automated fiber placement, and to study process improvements that could improve the processability of these materials. This paper will concentrate on the BMI materials, although other materials are being evaluated as well in the Cyanate Ester and Polyimide families.

Participation from three prominent BMI material vendors has been critical to the progress of this work. Each has been very helpful in advancing the state-of-the-art in these materials and supporting ATK with material evaluations on our automated fiber placement equipment. Each company has iterated on the processing characteristics of their respective material to allow us to better process it with automated fiber placement equipment.

A key part of the output of this work is time study data that is being used to compare the baseline BMI material being used on the JSF Wing Skins and Nacelles with the results achieved with the newer generation BMIs. ATK is under contract with Lockheed to fiber place the Upper Wing Skins and the Nacelles and is planning to use time study data on those parts to compare to demonstrations of these same parts with the newer BMI materials.

## 2. BMI MATERIALS EVALUATION

A literature search identified five BMI materials for evaluation. One of these materials, Cytec's 5250-4, is used as a baseline material for comparison throughout this study. The 5250-4 system is currently used in production on F22 and F35 fighter aircraft as well as in other applications. It has become the most widely used, high performance BMI in the aircraft industry. All of the materials considered are shown in Figure 2.1 under "Initial Plan".



**Figure 2.1 BMI Materials Evaluated**

In early discussions Hexcel (one of the material suppliers) recommended ATK not evaluate F655 for fiber placement, but concentrate on their newer version HX1616 (later called M65, shown in Figure 2.1). ATK took their recommendation and dropped F655 from further evaluations.

Cytec on the other hand provided two variations of 5250-X for consideration. One variation was 5250-X and the other 5250-XA. The -XA version proved to process better and performed slightly better in mechanical testing. The -X and -XA terminology were both dropped and a new designation of 5250-5 has been assigned to Cytec's new BMI. This is illustrated in Figure 2.1.

ATK ran fiber placement trials using each of the BMI's available, with support from the respective material supplier representatives. Each vendor was able to make iterations on their materials to improve tack and cleanliness of the materials as they run through the fiber placement machine. Each vendor supplied three separate iterations of their material for trials.

ATK built test panels from each of the vendor's materials for mechanical testing. All of these test panels were sent to an independent testing facility to be prepared and tested in the same general time frame. The test matrix selected was not a complete array of tests, but a set that ATK and AFRL felt gave a good comparison of the materials. The test matrix is shown in Table 2.1.

**Table 2.1 BMI Evaluation Test Matrix**

Material	Fiber Resin	IM7 5250-4	IM7 5250-4	IM7 5250-X	IM7 5250-X	IM7 5250-XA	IM7 5250-XA	IM7 M65	IM7 M65	IM7 RS8-HT	IM7 RS8-HT
Panel type		hlup	afp	hlup	afp	hlup	afp	hlup	afp	hlup	afp
0° tensile str, MPa		X	X	X	X	X	X	X	X	X	X
0° tensile mod, GPa		X	X	X	X	X	X	X	X	X	X
90° tensile str, MPa		X	X	X	X	X	X	X	X	X	X
90° tensile mod, GPa		X	X	X	X	X	X	X	X	X	X
0° compression str, MPa		X	X	X	X	X	X	X	X	X	X
0° compression mod, GPa		X	X	X	X	X	X	X	X	X	X
0° SBS str, MPa			X		X		X		X		X
350°F wet SBS, MPa			X		X		X		X		X
Quasi tensile str, MPa			X		X		X		X		X
Quasi tensile mod, GPa			X		X		X		X		X
Quasi compression str, MPa			X		X		X		X		X
Quasi compression mod, GPa			X		X		X		X		X
350°F wet Quasi tensile str, MPa			X		X		X		X		X
350°F wet Quasi tensile mod, GPa			X		X		X		X		X
350°F wet Quasi compression str, MPa			X		X		X		X		X
350°F wet Quasi compression mod, GPa			X		X		X		X		X
±45° in-plane shear str, MPa			X		X		X		X		X
±45° in-plane shear mod, GPa			X		X		X		X		X
350°F wet ±45° in-plane shear str, MPa			X		X		X		X		X
350°F wet ±45° in-plane shear mod, GPa			X		X		X		X		X

hlup = manual hand layup

afp = automated fiber placement

The results of the 0-degree lamina testing are summarized in Table 2.2. The Quasi-Isotropic and +/- 45 degree Shear, Laminate Data are summarized in Table 2.3.

<b>Tables 2.2 Lamina Properties on BMI Test Panels</b>										
<b>Material</b>	<b>5250-4</b>	<b>5250-4</b>	<b>5250-X</b>	<b>5250-X</b>	<b>5250-XA</b>	<b>5250-XA</b>	<b>M65</b>	<b>M65</b>	<b>RS8-HT</b>	<b>RS8-HT</b>
<b>Panel type</b>	<b>Hand</b>	<b>FP</b>	<b>Hand</b>	<b>FP</b>	<b>Hand</b>	<b>FP</b>	<b>Hand</b>	<b>FP</b>	<b>Hand</b>	<b>FP</b>
0° tensile str, MPa	2863	2918	2544	2718	2813	2727	2480	2783	2449	2393
0° tensile mod, GPa	161	164	161	161	161	163	160	157	166	167
0° tensile strain, %	1.6	1.6	1.46	1.57	1.57	1.54	1.38	1.6	1.36	1.32
90° tensile str, MPa	42	40	42	46	45	48	36	40	35	35
90° tensile mod, GPa	9	9	9	9	9	9	9	9	10	9
90° tensile strain, %	0.45	0.41	0.45	0.48	0.47	0.50	0.39	0.44	0.34	0.37
0° compression str, MPa	1162	1081	1140	1074	1112	1076	1185	1131	1152	1094
0° compression mod, GPa	143	139	146	138	146	138	142	141	151	142
0° compression strain, %	0.87	0.83	0.83	0.83	0.82	0.83	0.89	0.86	0.81	0.81
0° SBS str, MPa		118		117		118		111		110
350°F wet SBS, MPa		46		43		42		48		43

<b>Table 2.3 Quasi-Isotropic and +/-45 Degree Shear, Laminate Properties on Fiber Placed, BMI Test Panels</b>					
<b>Material</b>	<b>5250-4</b>	<b>5250-X</b>	<b>5250-XA</b>	<b>M65</b>	<b>RS8-HT</b>
Quasi tensile str, MPa	815.0	808.1	871.5	804.6	747.4
Quasi tensile mod, GPa	58.5	56.7	59.4	57.3	56.3
Quasi compression str, MPa	610.2	613.6	630.9	566.1	566.7
Quasi compression mod, GPa	55.6	53.6	55.8	53.5	54.2
350°F wet Quasi tensile str, MPa	804.6	799.8	821.2	741.9	703.3
350°F wet Quasi tensile mod, GPa	56.0	54.5	57.4	27.7	27.8
350°F wet Quasi compression str, MPa	402.0	446.1	442.6	459.2	492.3
350°F wet Quasi compression mod, GPa	54.9	51.7	53.4	51.4	51.8
±45° in-plane shear str, MPa	109.1	116.5	106.2	110.2	92.7
±45° in-plane shear mod, GPa	5.4	5.1	5.4	5.1	5.3
350°F wet ±45° in-plane shear str, MPa	82.0	77.9	72.3	74.4	73.2
350°F wet ±45° in-plane shear mod, GPa	2.4	2.1	1.8	2.4	2.9

A comparison of fiber placed properties to hand-layup control properties statistically shows there are very little differences between the two processes. See Table 2.4. There appears to be a slight drop in compressive properties (4-5%) in general. This is generally attributed to fibers not being quite as straight and true due to off-angle plies passing over more minor overlaps and gaps in underlying plies on fiber placed parts.

**Table 2.4 BMI Fiber Placed Properties Compared to BMI Hand Lay-up Properties Using Same Parent Tape**

Material	5250-4	5250-X	5250-XA	M65	RS8-HT
Panel type	FP	FP	FP	FP	FP
0° tensile str, MPa	+	+	+	+	+
0° tensile mod, GPa	+	+	+		+
90° tensile str, MPa	+	+	+	+	+
90° tensile mod, GPa	+		+	+	
0° compression str, MPa		+			+
0° compression mod, GPa				+	

0° Compression properties tended to be lower for fiber placed panels by 4-5%

**Scorecard, + = same\* or higher than comparable hand layup panel**

**= lower\* than hand layup panel**

**\*All decision based on statistical equivalency test**

ATK also compared fiber placed properties from the baseline 5250-4 material to the material properties generated from fiber placed panels made using the newer BMI materials (see Table 2.5). In general, the 5250-X, -XA materials were very close to the 5250-4 properties, as expected, since they are based on the same basic formulation. The M65 was a very close second with a few more properties falling slightly lower than 5250-4. The RS8-HT had a significant number of properties falling below that of 5250-4. However, all of the materials were still in very close range of 5250-4 properties.

**Table 2.5 New BMI Fiber Placed Properties compared to Baseline 5250-4**

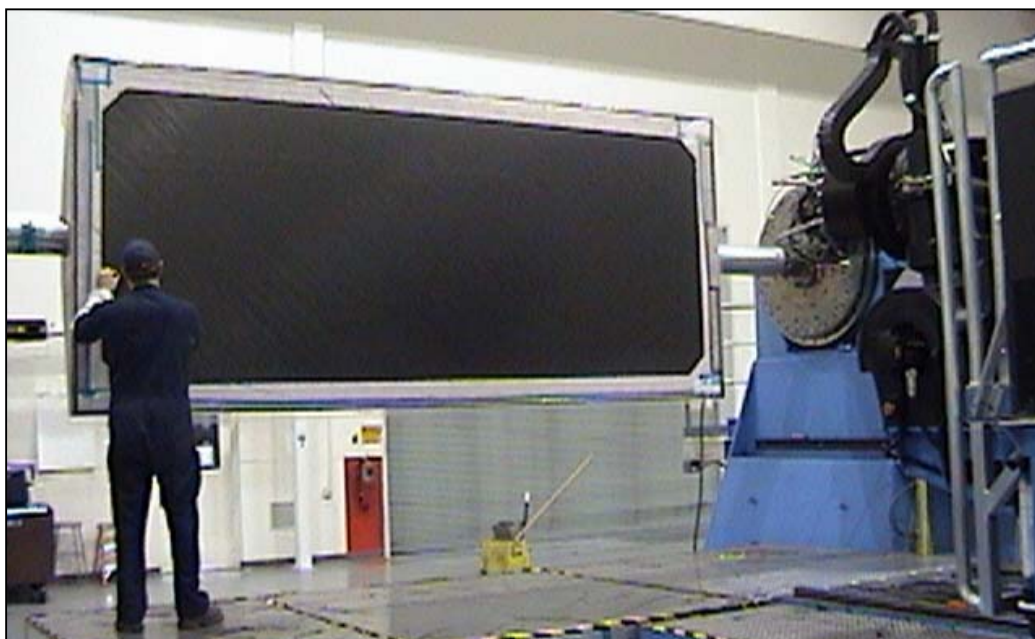
Material	5250-4	5250-X	5250-XA	M65	RS8-HT
0° tensile str, MPa	2916.5			+	
0° tensile mod, GPa	163.4	+	+		+
90° tensile str, MPa	40.0	+	+	+	
90° tensile mod, GPa	9.5		+		
0° compression str, MPa	1082.5	+	+	+	+
0° compression mod, GPa	139.3	+	+	+	+
0° SBS str, MPa	117.9	+	+		
350°F wet SBS, MPa	45.9			+	+
Quasi tensile str, MPa	815.0	+	+	+	
Quasi tensile mod, GPa	58.5		+		
Quasi compression str, MPa	610.2	+	+		
Quasi compression mod, GPa	55.6		+		
350°F wet Quasi tensile str, MPa	804.6	+	+		
350°F wet Quasi tensile mod, GPa	56.0	+	+		
350°F wet Quasi compression str, MPa	610.2	+	+	+	+
350°F wet Quasi compression mod, GPa	8.1		+		
±45° in-plane shear str, MPa	15.8	+	+	+	
±45° in-plane shear mod, GPa	0.8		+		+
350°F wet ±45° in-plane shear str, MPa	11.9				
350°F wet ±45° in-plane shear mod, GPa	0.3	+		+	+

**Scorecard, + = same\* or higher than 5250-4 baseline**

**= lower\* than 5250-4 baseline panel**

**\*All decision based on statistical equivalency test**

A large test panel was designed to exercise the machine and allow for time study data to be taken on each material as it was processed through the fiber placement machine (see Figure 2.2). This large time study panel was 3.81 meters (12.5 ft) long by 1.68 meters (5.5 ft) tall and comprised of 8 plies of material. The layup sequence was quasi-isotropic (+45, 0, -45, 90, 90, -45, 0, +45).



**Figure 2.2 Large Time Study Test Panel**

The time study data included: 1) time the FP machine was operating, 2) time spent cleaning the machine to keep it running, and 3) time to repair plies that were missing tows due to plugged up chutes, lack of tack, etc. The results are summarized in Table 2.7. Multiple runs were performed with each material using the data from the third iteration on materials from each vendor in the down-select process.

<b>Table 2.7 IM7/BMI Slit Tape Process Comparison (Peak Rate and Time Study Parameter)</b>				
BMI Materials Evaluated (3rd iteration)	Cytec 5205-4	Cytec 5205-5	Hexcel M65	YLA RS8-HT
Peak Rate Achieved (cm/sec)	30.5	76.2	76.2	35.6
Average On-Part Rate Achieved (cm/sec)	9.6	15.0	15.2	6.1
Panel Time Study Parameter (1-10)	1.92	8.88	10	1
1 = Worst (highest overall time to build panel) 10 = Best (lowest overall time to build panel)				

Each of the materials was also evaluated based on current cost and projected cost given larger quantities. The exact pricing will be kept confidential for the suppliers, but a comparative figure is given for each material to allow this to be used as a down-select criterion for moving from 5 materials to 2 materials in the final phase of the program. The results are shown in Table 2.8.

<b>Table 2.8 IM7/BMI Slit Tape Cost Comparison at differing Quantities (in scaled parameters)</b>				
BMI Resin Matrix prepregged on IM7 Fiber, tape slit to 3.18 mm	Small Dev Run Actuals	Medium 454 kg quote	Large 4536 kg quote	S/M/L at 30/50/20 Weighting
Cycom 5250-4	4.70	5.60	7.20	5.65
Cycom 5250-5	4.70	5.60	7.20	5.65
Hexcel M65	6.60	4.80	9.60	6.30
YLA RS8-HT	1.00	4.10	6.30	3.61
Note: Lowest price material gets highest number rating				
Scale	Highest pricing = 1 Lowest pricing = 10			

### 3.0 FIBER PLACEMENT PROCESS IMPROVEMENT

#### 3.1 INTRODUCTION

In addition to evaluating new BMI materials and working with the material suppliers to improve the processing characteristics, ATK took on the challenge of finding ways to improve the FP process to better handle the current BMI materials with their associated problems. The main problems being:

1. Lack of Tack
2. Resin and fiber fuzz build up in the fiber redirects and delivery system

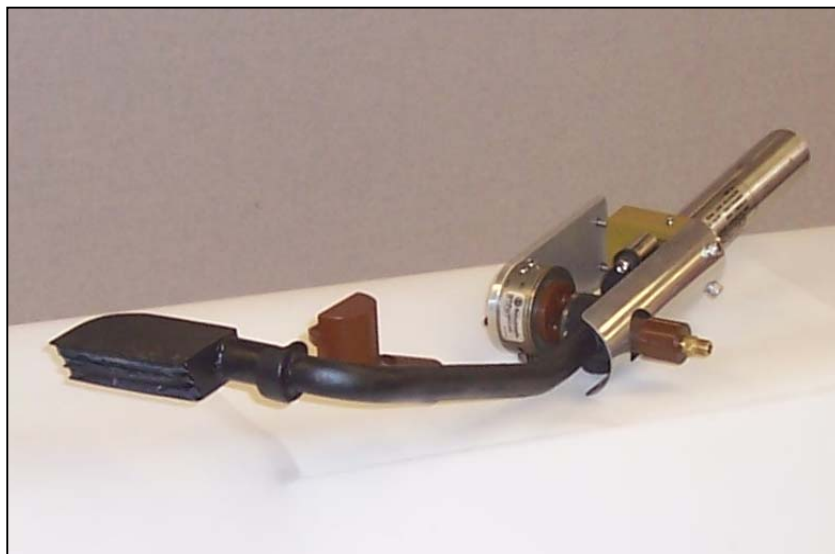
#### 3.2 IMPROVED TACK

The lack of tack is still being addressed, but two improvements have helped the situation. First, a study of humidity vs. tack was conducted to find an optimum processing humidity. The other improvement has been to increase the compaction point heating capability to allow the process to run hotter at high laydown rates.

The humidity studies show that the tack on BMI resins increases as the relative humidity increases. The practical level to run is still being determined, as the humidity can adversely affect other elements of the process and equipment such as the interleaf removal system. Processing at 40% RH has been established as a baseline for the time being at ATK. Work at higher humidity levels are being studied. The other interesting information gathered is that the

slit BMI tape material absorbs moisture and gives it back up relatively quickly. Within a 1-2 hour period 5250-4 stabilizes to the environment it is in (this does not include the effect the interleaf may have letting the moisture escape or be absorbed).

The compaction point heating unit, upper limit on source temperature, has been increased by 149 degrees C (300 F) on ATK equipment. Raising the supply temperature required a change in some of the piping and valves to control the hotter gases. The gas temperature is ramped up and down with fiber laydown speed to compensate for the lack of residence time at higher speeds. Figure 3.2.1 shows the improved nip-heating device being implemented.



**Figure 3.2.1 Compaction Point Heating Device for FP Process**

### **3.3 MATERIAL CLEANLINESS IN FP SYSTEM**

Dealing with the fiber and resin build-up (called “fuzz”) has proven to be a larger challenge and is still being worked. ATK discovered that much of the fuzz is generated as a result of the parent prepreg tape not being fully impregnated. When the parent prepreg tape material is then slit into narrow tape for fiber placement the slit exposes dry fiber on both sides of the slit tapes. When these dry fibers rub against anything in the redirect process the cut pieces of dry fiber at the edges accumulate on various features in the redirect system and in the delivery head itself. The dry fibers and resin dust accumulate together into nasty fuzz balls that will eventually clog up the chutes that the tows pass through in the delivery head. As the pathways get clogged, the tows will not re-feed to the part surface properly after they have been cut. Figures 3.3.1 – 3.3.3 show examples of the fuzz build-up at various locations.

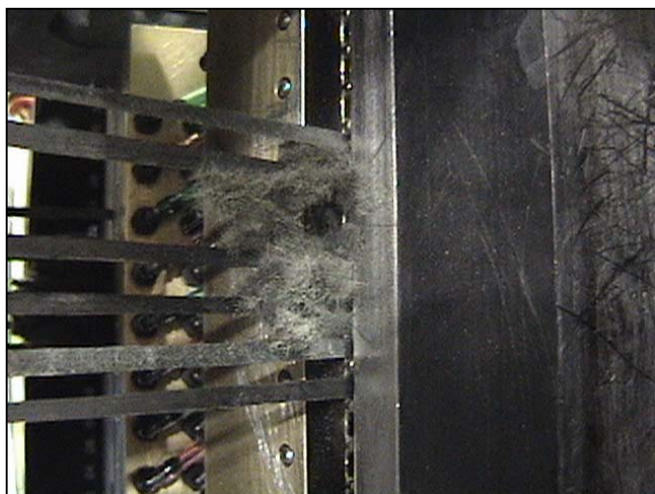


Figure 3.3.1 Fuzz At Tray Entry, 1 Tow Missing



Figure 3.3.2 Fuzz At Tray Entry After Full Ply Of Material Was Fiber Placed

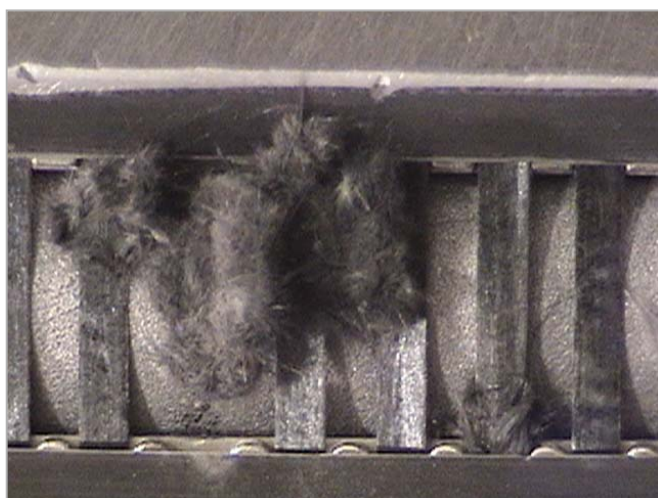


Figure 3.3.3 Fuzz Build Up In Tow "Add" Zone

ATK collected fuzz from various points on the fiber placement machine with each of the materials during the first iteration on the 5 BMI materials. All of the materials had an unacceptable amount of fuzz and a considerable amount of work was done by each vendor in iterations 2 and 3 to reduce the amount of fuzz generated. Figure 3.3.4 shows what was collected from each material during processing of a given set of test panels using the first iteration of material from each vendor. ATK had the most trouble with the YLA's BMI and then the baseline Cytec 5250-4, with the best being the two variation of Cytec's 5250-5 and Hexcel's M65.



Figure 3.3.4 Fuzz collected on each BMI material during test panel fabrication

These fuzz balls caused the operator to shut down the process to clear the chutes and re-thread the slit tapes. This is referred to as machine down time. Other negative effects includes rework time to replace the missing tows on the part surface, and rework time to pick out any fuzz balls that pass through the head onto the part, see Figure 3.3.5. These are referred to as rework time.



Figure 3.3.5 Fuzz that has passed through FP head and is trapped in the laminate

ATK is working on methods of collecting the fuzz prior to the materials entering the delivery head, so that cleaning can be done at more planned intervals such as between plies. ATK is also experimenting with methods of passing the fuzz on through the head instead of letting it collect at the tray entries. This may just pass the problem on to other collection points, but ATK is setting up to evaluate the effectiveness of this approach.

### 3.4 DEMONSTRATION

As a final demonstration article in this program a large aircraft part will be fabricated using the best BMI material selected from the material evaluation phase. Where ATK is already moving forward to fabricate an upper wing skin using the baseline 5250-4 material under the JSF contract, it provides an excellent opportunity to cross utilize the same tool and repeat that article using the preferred BMI from this program.

This will allow a direct time study comparison of the improved fabrication time achievable with these new BMI formulations. Improvements to the Fiber Placement System will also be implemented and time studied. The overall goal is to show a 3X improvement over the rates

achieved on the first BMI Upper Wing Skins produced with the fiber placement process under the Development Phase of the JSF program (see Figure 3.4.1 below).



**Figure 3.4.1 Fiber Placed JSF Upper Wing Skin in Inspection Fixture**

## 4. SUMMARY

Two new BMI materials have emerged as front-runners for future high performance aircraft parts built using automated fiber placement. Cytec's new 5250-5 and Hexcel's new M65. Both of these materials have allowed increased rates and decreased down time in aircraft part fabrication. The tack is better and the cleanliness of the material is better than the baseline 5250-4 material currently being used on the JSF program. Mechanical testing to date has shown both to be close performers to the baseline 5250-4 material. Overall, in mechanical properties, the 5250-5 performed slightly lower than -4 and M65 performed slightly lower than -5, but both were very respectable in the tests performed. A comparison of 5250-5 properties and M65 Properties, listed in Table 4.1, shows the relative strengths and weaknesses of each. As can be seen, the majority of properties are within 5% of one another.

**Table 4.1 Comparison of 5250-5 and M65  
Mechanical Fiber Placed Properties**

<b>Material</b>	<b>5250-XA</b>	<b>M65</b>	<b>-XA/M65</b>
0° tensile str, MPa	2726.7	2783.4	98%
0° tensile mod, GPa	162.7	156.9	104%
90° tensile str, MPa	47.6	40.5	118%
90° tensile mod, GPa	9.4	9.1	103%
0° compression str, MPa	1075.7	1130.7	95%
0° compression mod, GPa	138.1	140.7	98%
0° SBS str, MPa	117.9	111.4	106%
350°F wet SBS, MPa	41.7	48.1	87%
Quasi tensile str, MPa	871.5	804.6	108%
Quasi tensile mod, GPa	59.4	57.3	104%
Quasi compression str, MPa	630.9	566.1	111%
Quasi compression mod, GPa	55.8	53.5	104%
350°F wet Quasi tensile str, MPa	821.2	741.9	111%
350°F wet Quasi tensile mod, GPa	57.4	55.4	103%
350°F wet Quasi compression str, MPa	442.6	459.2	96%
350°F wet Quasi compression mod, GPa	53.4	51.4	104%
±45° in-plane shear str, MPa	106.2	110.2	96%
±45° in-plane shear mod, GPa	5.4	5.1	105%
350°F wet ±45° in-plane shear str, MPa	72.3	74.4	97%
350°F wet ±45° in-plane shear mod, GPa	1.8	2.4	73%

Shaded blocks indicate instances where -XA properties were >5% higher than M65

Shaded blocks indicate instances where M65 properties were >5% higher than -XA

It appears M65 has the best projection for long range cost effectiveness at this early evaluation date. Down-select data leading to the selection of these two materials for further evaluation is shown in Figure 4.1.

### Processability, Mechanical Properties and Cost Used in Down-Select

	PROCESS				PROPERTIES				COST				TOTAL	RANK
	Rank 1 - 10 (1 - Worst)		Weighting	Total	Rank 1 - 10 (1 - Worst)		Weighting	Total	(1 - Worst)		Weighting	Total		
<b>YLA</b>														
<b>RS8-HT</b>	1	x	5	= 5	1	x	4	= 4	3.6	x	3	= 10.8	<b>20</b>	4
<b>CYTEC</b>														
<b>5250-4</b>	1.92	x	5	= 9.6	10	x	4	= 40	5.7	x	3	= 17.1	<b>67</b>	3
<b>5250-X</b>	8.88	x	5	= 44.4	6.08	x	4	= 24.3	5.7	x	3	= 17.1	<b>86</b>	1
<b>HEXCEL</b>														
<b>M65</b>	10	x	5	= 50	2.48	x	4	= 9.92	6.3	x	3	= 18.9	<b>79</b>	2

### Top Two BMIs down-selected to carry forward

1. Cytec 5250-X
2. Hexcel M65

**Figure 4.1 Down-Select Matrix Used To Carry Two BMIs Forward for Further Evaluation**

A future aircraft specification allowing either of these materials to be used would provide the best scenario for the government and fabricators, having two competitive material suppliers to choose from. More work will need to be done to develop a full database of allowables for each material to make this happen on current aircraft programs.

ATK and AFRL will complete this study and build the large demonstration article in the fall of 2006. At that point we will have a good feel for the cost savings potential using at least one of these new materials and process improvements to the automated fiber placement process.

The intent of the Air Force and ATK is to provide data to support the selection of the next generation BMI material(s) for use in future fighter aircraft and unmanned aerial vehicles (UAVs), allowing a high degree of automation to be utilized.

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